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Simulating building thermal behaviour: the case study of the School of the State Forestry Corp

Maurizio Carlini[a,*], Domenico Zilli[b], Elena Allegrini[a]

[a]*University of Tuscia, via San Camillo de Lellis snc, 01100 Viterbo, Italy*
[b]*CIRDER, via Santa Maria in Gradi 4, 01100 Viterbo, Italy*

Abstract

The building thermal performance plays a fundamental role in reducing the national energy consumption, especially considering that the majority of the existing structures were built before energy efficiency was a concern at all. The paper presents the case study of the School of the State Forestry Corp in Sabaudia (Italy).The aim is to simulate the thermal behaviour both in stationary and dynamic conditions, and to identify the most appropriate action to improve the building energy efficiency, ensuring occupants' thermal comfort during the year. The results clearly show that considerable thicknesses of insulating material do not represent an advisable retrofitting in summer.

Keywords: heat transfer; buildings; dynamic simulation; TAS software; economical assessment.

1. Introduction

Buildings account for approximately 40% of energy consumption in the European Union (EU), 63% of which is attributed to the residential sector. Thus, it has become a relevant environmental issue, especially if we consider that buildings constitute a major pollution source: CO_2 from residential buildings represents the fourth largest source of greenhouse gases (GHG) emissions in the EU, contributing to 10%. The average energy consumption in Europe has recently reached 200 kWh/m^2/year [1-8].

* Corresponding author. Tel.: +39-0761-401343; fax: +39-0761-401343.
E-mail address: maurizio.carlini@unitus.it.

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Nomenclature

CFD	Computational Fluid Dynamics
EP_{DHW}	total primary energy consumption for domestic hot water (kWh/m^2/year)
EP_{GL}	global energy performance indicator for winter heating (kWh/m^2/year)
EP_W	energy performance indicator for winter heating (kWh/m^2/year)
Φ_{int}	heat flux entering the system
Φ_{out}	heat flux leaving the system
Φ_{source}	heat flux of an eventual heat source
Φ_{stock}	stored heat flux

Reducing the energy demand and exploiting Renewable Energy Sources (RES) represent a reachable target in the built environment so that building sustainability is a fundamental tool to provide healthy and comfortable indoor conditions, limiting the impacts on Earth's natural resources. Since the majority of existing structures were built before energy efficiency was a concern at all and most of them will be in function at least until 2025, retrofitting the existing building stock has a large potential for improving energy performance and decreasing pollutant emissions [9].

Energy renovations have positive implications and benefits not only in GHG emissions reduction and energy savings, but also in social and financial aspects, e.g. fuel poverty. In this scenario, the updated version of the Energy Performance of Buildings Directive (EPBD) has been recently published by the European Commission and focuses on the need for the Energy Efficient Retrofitting (EER) of existing buildings. EER is aimed at reducing the total energy demand, simultaneously ensuring the required levels of occupants' thermal comfort, and encompasses several actions, such as installation of thermal insulation, limitation of thermal bridges, and use of mechanical ventilation with heat recovery. Accordingly, all the aspects starting from the design phase need to be optimized in order to comply with the current regulations. Practical and scientific solutions have been proposed: an awareness campaign with the occupants identifying simple actions in order to significantly decrease the end-use energy consumption; optimization of energy systems, including the integration of renewable solutions; control and monitoring systems, allowing controlled blackouts during specific moments of the day [2, 4, 5].

The role and importance of energy efficiency has been also underlined by the Directive 2012/27/EU, which establishes a common framework of measures for achieving the Union's 2020 headline targets and requires each Member State to identify reference case studies for minimum energy performance. Furthermore, since buildings owned by public bodies represent a considerable share of the building stock, renovation strategies need to be investigated for this sector. This becomes even more important if we consider that the average efficiency of public bodies' buildings is 50%, where the amount of primary energy losses reaches 6.5 Mtep (figure 1) [7, 10].

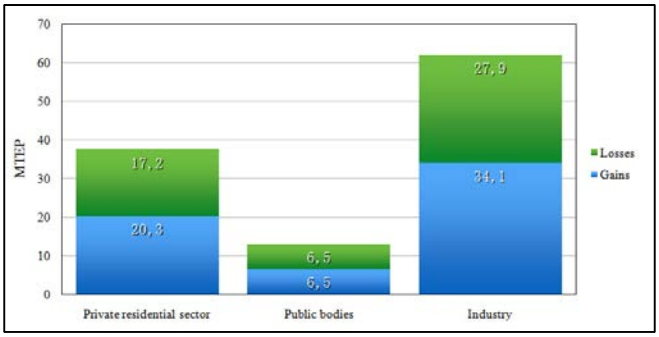


Fig. 1: Share of losses and gains in the private buildings, public bodies' buildings and industry [10]

Energy saving regulations originated in cold climates, where the fundamental concern is to reduce the winter energy consumption for space heating and to prevent heat loss through the building, having a stationary behaviour during the year. Thus, following the European trend, Italy set limits for stationary and periodic parameters in new constructions or when renovating existing buildings, as laid down by the Legislative Decree 192/05 and its subsequent directives [7].

Nevertheless, since daytime and seasonal temperature strongly vary, the Italian temperate climate is dynamic: in the winter, the use of considerable thicknesses of insulation is a correct solution, hindering the outgoing heat flux; in the summer or during mid-seasons, walls with considerable heat capacity and with limited insulation should be preferred in order to reduce the thermal peaks during the hottest hours and releasing the heat stored during the night. Thus, considerable thicknesses of insulating material lead to the problem of overheating, creating the thermos effect and impeding the outgoing heat flux [7].

The paper presents the possible retrofitting actions for an existing building in Italy, considering the quasi-stationary and dynamic behaviour. The results demonstrate the importance of dynamic analyses in choosing the best opportunity of energy saving in renovating existing structures, especially in the Mediterranean climate.

2. Material and methods

2.1. Physical models to simulate building thermal behaviour

Different physical models are used to describe the building thermal behaviour depending on their specific needs, including space heating, ventilation, air conditioning systems, occupants behaviours, use of RES, and financial aspects. The physical building performance is based on the solving of the heat transfer differential equations, which can be written in terms of the energy conservation law [8]:

$$\Phi_{\mathrm{int}} + \Phi_{source} = \Phi_{out} + \Phi_{stock} \tag{1}$$

where the principal in- and out- coming fluxes are due to the conduction through the walls, the convection, the longwave and shortwave radiation, and the ventilation. A large number of numerical softwares are nowadays available to solve such physical problems, both in stationary and dynamic conditions. The steady state approach is commonly used to assess the building energy performance and leads to long-term analyses of different scenarios thank to their fast calculations. However, a considerable limitation occurs since the inertia of the building envelope is completely neglected. Hence, dynamic thermal models should be preferred when analysing energy saving solutions [2, 8].

The building thermal models are divided into three different typologies, namely the multizone, the zonal and CFD methods, each of one has its own application depending on the specific problem. The present paper involves the use of the first approach (figure 2), which is based on the following assumption: each building zone is a homogeneous volume with uniform state variables and may be approximated to a node that is described by a unique temperature, pressure, etc. A node may represent a room or the exterior of the building itself or a load. This technique is capable to describe the behaviour of a multiple zone building in a very limited computational time and is particularly useful in evaluating the energy consumption and the time evolution of temperature within a room [8].

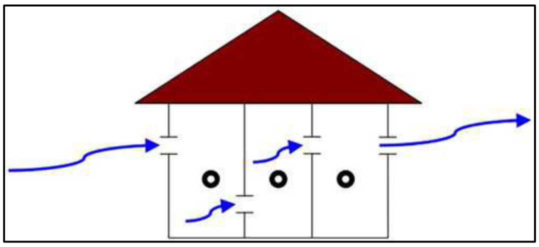


Fig. 2: Schematic representation of a problem solved with the multizone method [8].

2.2. Description of the case study

The existing structure is a multi-storey building owned by the School of the State Forestry Corp in Sabaudia (Central Italy, Province of Latina), containing offices, bedrooms, kitchens, and rooms. It was built at the beginning of 1950s and will be renovated in those areas within the red rectangle in the floor plan shown in figure 2 and including the buildings denoted with the capital letters E, F, and G. General data on the building and its conditioned space and volume are given in tables 1 and 2.

The building consists of 17 typologies of single or double glass windows with aluminium frame. The overall thermal transmittance of the transparent enclosures is calculated according to the analytical method reported in UNI 10077 and varies depending on the considered typology. The total dispersion surface towards the external environment accounts for 5498 m^2, of which the vertical dispersion represents the most significant amount, consisting of 2785 m^2 (51%). The external walls are made of solid brick masonry without any insulation cover, while the internal walls are made of 12 mm-thick bricks and 2 mm of internal and external plaster. The roof consists of concrete elements with a waterproof layer and the tiles are finished with majolica. The thermal transmittances of the opaque and transparent enclosures are reported in table 3.

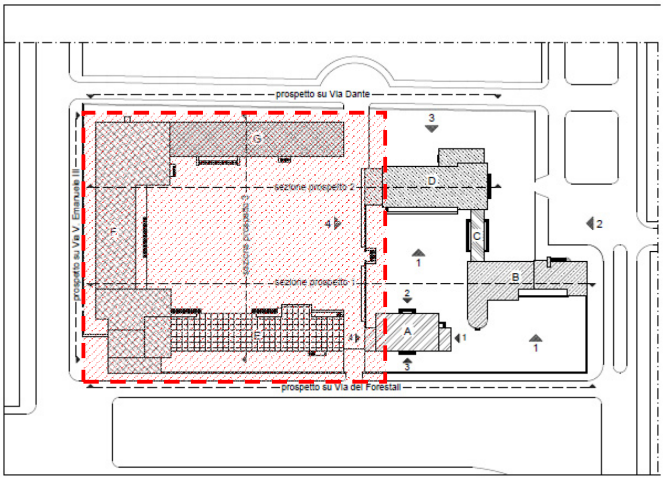


Fig. 3: Plan of the existing building and buildings to be renovated.

Table 1. General data on the building.

Use classes	Residential
Category of use classes	E.1 according to the Presidential Decree 412/93
Latitude/Longitude	41,3001 N/ 13,0317 E
HDD	1171 according to the Presidential Decree 412/93
Duration of the heating period	November 15 – March 31
Number of heating days	136
Climatic zone	C according to the Presidential Decree 412/93

Table 2. Conditioned space and volume.

Floor area	1833 m^2
Gross conditioned space	3766 m^2
Net conditioned space	2636 m^2
Conditioned volume	11 006 m^3
Ratio S/V	0.5 1/m

Table 3. Thermal transmittance of opaque elements.

Material	Thermal transmittance U ($W/m^2/K$)
External wall	1,433
Internal wall	1,921
Roof	1,967
Windows	5 (minimum value)

Considering the use class of the building and complying with the Presidential Decree 412/93, the set point for the indoor temperature is given by 20 °C in winter and 26 °C during summer. Both values ensure thermal comfort within the built environment. With specific regard to the outdoor conditions, the external air temperature is assumed equal to 2°C in winter according to UNI 5364 and to 33 °C during summer following UNI 10339. The glass temperature can be considered constant if its thickness is limited: however, it depends on thermal irradiation on vertical surface during hot seasons.

2.3. Stationary and dynamic modelling of the building

The energy audit of the building was carried out in MC11300, a commercial software complying with the requirements laid down by the Comitato Termotecnico Italiano (CTI) and national regulations, and led to the Energy Performance Certificate (EPC) [11]. Accordingly, several indicators were calculated, namely EP_{DHW}, EP_W, and EP_{GL} of the whole building for different scenarios following the quasi-stationary approach (table 4):

a) asset rating, which is based on standard weather conditions and building use (referred to as "EX ANTE STD");
b) tailored rating, which is based on the measured energy use and takes into account how the building itself is managed and used. Monthly energy and thermal consumptions are available for 2010, 2011 and the first semester of 2012 and show that the standard values coming from a) exceed real consumptions up to 35%. Thus, in order to correct the asset rating, the occupancy of the building was considered and led to calculate the number of heating days (corresponding to 100 instead of 136 as it is in the asset rating). The number of heating hours has been modified and assumed equal to 10. The different scenarios belonging to b) are denoted by the two letters "TR" and are referred to the current situation of the building ("EX ANTE TR") and to the suggested energy saving opportunities ("ESO TR").

Table 5 gives information about some environmental issues, such as the amount of CO_2, CO_2 savings, and the energy savings and improvement for each scenario. Table 6 shows the economical feasibility of each single action in terms of payback time for the suggested improvement: two situations are taken into account, depending on the possibility to benefit the national incentives on energy efficiency improvement (Ministerial Decree 28/12/2012).

Table 4. Energy class of the building.

Scenario	Description	EP_{DHW}	EP_W	EP_{GL}	EPC
EX ANTE STD		3,146	35,356	38,502	G
EX ANTE TR		2,28	27,003	29,285	G
ESO 1 TR	8 cm insulating material	2,28	19,057	21,338	F
ESO 2 TR	10 cm insulating material	2,28	18,710	20,992	F
ESO 3 TR	12 cm insulating material	2,28	18,466	20,748	F
ESO 4 TR	Mounting of new windows	2,28	19,691	21,972	F
ESO 5 TR	New windows only at floor 1	2,28	23,690	25,972	F
ESO 6 TR	ESO 2 + ESO 5 + 14 cm insulating material (roof)	2,28	8,006	10,287	C

ESO 7 TR	ESO 2 + 14 cm insulating material (roof)	2,28	11,096	13,378	D
ESO 8 TR	14 cm insulating material for the roof	2,28	19,493	21,774	F
ESO 9 TR	Regulating valves substitution	2,28	25,901	28,182	G
ESO 10 TR	Installation of a condensing heat generator	2,28	20,516	22,797	F
ESO 11 TR	ESO 8 + ESO 10	2,28	14,788	17,069	E

Table 5. Environmental parameters.

Scenario	CO_2 emissions (kg CO_2/m^2/year)	CO_2 emissions saving (kg)	Energy saving (kWh)	Energy improvement (%)
EX ANTE TR	55,472			
ESO 1 TR	39,732	36.071	144.285	27
ESO 2 TR	39,067	37.827	151.310	28
ESO 3 TR	38,599	38.941	155.766	29
ESO 4 TR	41,363	32.364	129.459	24
ESO 5 TR	48,625	15.088	60.351	11
ESO 6 TR	18,523	86.690	346.761	65
ESO 7 TR	24,555	72.594	290.377	54
ESO 8 TR	40,570	34.384	137.537	25
ESO 9 TR	52,87	4.992	19.970	3,7
ESO 10 TR	42,532	29.583	118.334	22
ESO 11 TR	31,540	55.737	222.950	42

Table 6. Economical assessment: costs and payback time of the investment.

Scenario	Cost (€)	Yearly saving (€)	Payback time without incentives (years)	Payback time with incentives (years)
EX ANTE TR				
ESO 1 TR	153.250	12.100	12/13	NO
ESO 2 TR	168.200	12.600	13/14	7/8
ESO 3 TR	183.800	13.000	14/15	8/9
ESO 4 TR	290.000	10.800	26/27	22/23
ESO 5 TR	140.000	5.050	27/28	18/19
ESO 6 TR	410.500	28.900	14/15	8/9
ESO 7 TR	271.800	24.250	11/12	6/7
ESO 8 TR	103.600	11.500	8/9	5/6
ESO 9 TR	7.500	1.670	4/5	NO
ESO 10 TR	45.000	9.870	4/5	2/3
ESO 11 TR	148.600	18.600	7/8	4/5

The quasi-stationary approach led to define the 4 most compelling scenarios among those above-mentioned in table 4-6, depending on the level of energy improvement, the initial costs, and payback time of the investment. In order to identify the most appropriate retrofitting for the existing building, a dynamic simulation was carried out in TAS Engineering (Thermal Anlysis Software) developed by EDSL. It has a modular design and is split into three different main parts: the 3D Modeller, the Building Simulator and the Results Viewer [12].

After building the geometry of the problem and the surrounding elements (figure 4, left), the whole volume was divided into 87 thermal zones (figure 4, left). The first step consisted on the calculation of the primary energy need for the current situation and suggested scenarios (ESO 2, ESO 8 and ESO 2 + ESO 8) as it is shown in figure 5: the insulation of the roof together with an external insulation of the walls (ESO 8 + ESO 2) has the lowest heating and cooling energy primary demand. Moreover, it can be noted that ESO 8 leads to a better thermal behaviour than ESO 2 for cooling, i.e. in summer conditions. Accordingly, a considerable thickness of the insulating material (ESO 2) is characterized by a good thermal behaviour in winter and very similar to ESO 8, but during the summer the insulation of the roof leads to a better performance.

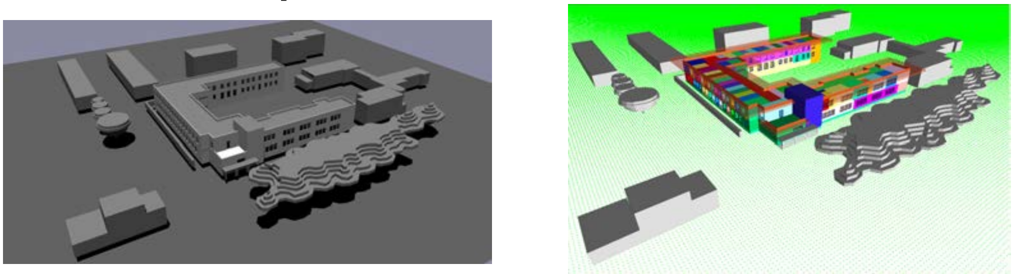
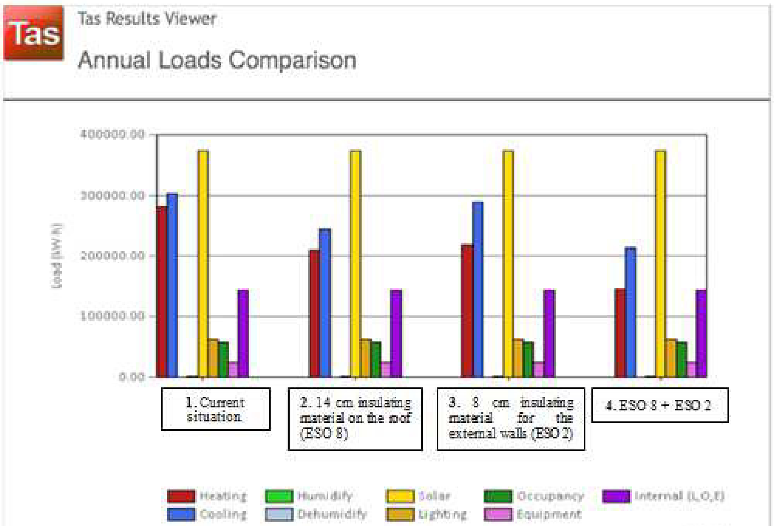


Fig. 4: Geometry of the problem and surroundings elements (left) and the thermal zones of the building (right).



	Heating	Cooling	Humidify	Dehumidify	Solar	Lighting	Occupancy	Equipment	Internal (L,O,E)
1.	281237,0	302535,8	0,0	1615,5	374459,3	61876,1	57163,3	23884,9	142924,3
2.	210426,7	244333,2	0,0	1723,3	374459,3	61876,1	57163,3	23884,9	142924,3
3.	218698,6	289964,4	0,0	1716,2	374459,3	61876,1	57163,3	23884,9	142924,3
4.	144881,7	213240,8	0,0	1705,9	374459,3	61876,1	57163,3	23884,9	142924,3

Fig. 5: Annual loads comparison between the current situation and different scenarios.

Table 7 shows the heating and cooling demand both in quasi stationary and dynamic conditions, generated by the building simulation in MC11300 and TAS Engineering respectively. In winter conditions, the results are in good agreement and do not significantly differ, while during the summer considerable differences between the two approaches occur.

Table 7. Comparison between the quasi-stationary and dynamic approach.

Scenario	Heating (kWh)		Cooling (kWh)	
	Quasi-stationary approach	Dynamic approach	Quasi-stationary approach	Dynamic approach
Current situation	307000	281000	135000	302000
ESO 8	221757	218678	121251	244333
ESO 2	213202	210441	164130	289964
ESO 2 + ESO 8	129335	144833	154032	213240

The previous result emerging from the analysis of the primary energy is also confirmed if we consider the occupants' thermal comfort. Figure 6 shows the number of days during the year in which the internal temperature exceeds 26 °C: it can be seen even in this case that insulating the roof (grey bar) ensures a better behaviour than the insulations of the external walls (yellow bar).

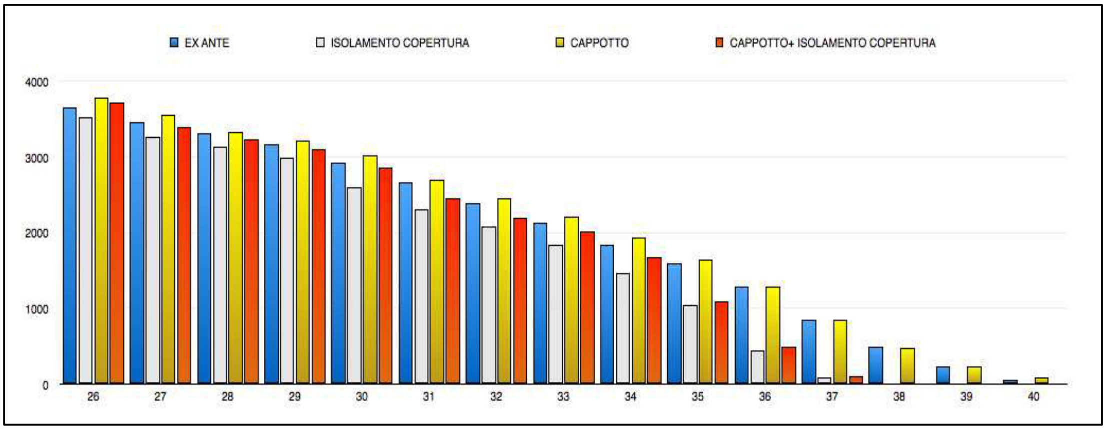


Fig. 6. Number of days in which the temperature is higher than 26 °C.

3. Conclusion

A comparison between the quasi-stationary and dynamic approach for describing the building thermal behaviour has been proposed in the present paper. The simulations for the School of the State Forestry Corp clearly show that the most appropriate opportunity of energy saving in renovating existing buildings can be correctly defined by a dynamic approach, taking into account the thermal inertia and the internal gains. Although a significant difference does not exist during winter, in the summer and mid-seasons this technique should be preferred.

Although the steady state approach comply with the current regulations, dynamic modelling should be developed when retrofitting in order to evaluate the thermal behaviour during the whole year, especially in the Mediterranean climate.

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